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AN EXPERIMENTAL STUDY ON PREDICTION OF SURFACE ROUGHNESS IN GRINDING

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ABSTRACT

This article presents a study of surface roughness prediction of a part when grinding conducts an overview study of certain published works on predicting the surface roughness of parts when grinding. Through the analysis of such works, the roughness prediction modeling method based on the analysis of the performance probability of the cutting process has many advantages and has been performed by many authors. All the studies of this type, show the relationship between surface roughness and undeformed chip thickness. However, in those studies, the relationship between surface roughness and undeformed chip thickness also showed different results. The main reason for this is that when they developed surface roughness models, they had different assumptions. This study carried out the process of grinding some common steels (SKD11, SUJ2, 3X13 and C45) with two common grinding wheels (aluminum oxide grinding wheel and CBN grinding wheel), from which to determine the surface roughness prediction model suitable for each specific case.

KEYWORDS: Prediction of Surface Roughness, Undeformed Chip Thickness, Grinding Process & Modeling

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Original Article

1. INTRODUCTION

Like other cutting and processing methods, the quality of the surface when grinding is assessed through many parameters such as hardness, surface layer residual stress, surface roughness, etc. In particular, the surface roughness of the part is one of the parameters that greatly affects the working ability of the part and is often chosen as an indicator to evaluate the grinding process [1]. When studying the grinding process with the desire to process the surface of machine parts with small roughness, there have been many studies conducted by empirical methods. However, when conducting experimental researches, there are usually certain limitations. ***Firstly***, empirical research results are usually only applied to certain specific cases. ***Secondly***, the cost of experimental research is quite expensive, thereby affecting the efficiency of the grinding process [2, 3].

To partially overcome the limitations of experimental research, there have been a number of modeling and simulation studies for simulating surface roughness published. Lal and Shaw [4] conducted a model to predict surface roughness when grinding based on a model analysis of the thickness of a cut. In the studies [5, 6, 7], the authors conducted the prediction of surface roughness when grinding with the assumption that the abrasive grains are evenly distributed on the surface of wheel. Zhou *et al*. [8] studied the prediction of surface roughness by grinding by determining the average value of the depth of the cut into the machining surface of abrasive grains ... However, according to Hecker *et al*. [3], the roughness value as predicted in such studies is often not close to the experimental results, because there are many parameters during the experiment unlike the assumptions that the studies have made.

The application of probability theory when analyzing the cutting process of the abrasive grains involved in cutting to predict surface roughness has also been conducted by a number of studies. Basuray *et al.* [9], Steffens [10] predict rough surfaces with the assumption that the grinding process is a mechanical–thermal equilibrium process. However, according to Hecker *et al.* [3], the applicability of the above research results is quite difficult because of the microstructure of the rock surface.

When analyzing the grinding process, assuming that the cross section of the cut created by each abrasive grains left on the surface workpiece is a triangular shape, Hecker *et al.* [3] have built surface roughness model of the part as eq. (1).

$$R_a = 0.37\, h_m \tag{1}$$

In which, h_m is the undeformed chip thickness (in Appendix 1). The value of h_m depends on many factors, such as the grinding parameters, the characteristics of the grinding wheel and the grinding method. The determination of h_m values is detailed in the study of Anne Venugopal *et al.* [11].

Sanjay Agarwal *et al.* [12] also proceeded in the same manner as Hecker but assumed that the cross section of scratches of each abrasive grain left on the surface of the part was semi-circular shape, further assuming that the diameter of the abrasive grain is twice the depth of cut and the undeformed chip thickness is equal to the depth of cut. From this, they formulated the relationship between surface roughness and undeformed chip thickness as eq. (2).

$$R_a = 0.423\, h_m \tag{2}$$

In another study, Sanjay Agarwal *et al.* [13] assumed that the cross section of scratches of each abrasive grain left on the surface of parts has parabolic form. Since then, they have built eq. (3).

$$R_a = 0.396\, h_m \tag{3}$$

In the same approach as the method, Hecker *et al.* [3], Sanjay Agarwal *et al.* [12, 13] performed, Sanchit Kumar Khare *et al.* [14] also assumed that the cross section of the scratches of each abrasive brain left on the surface part is of a semi-circular shape, and also assuming that the diameter of the abrasive brain is twice the depth of the cut, the undeformed chip thickness is equal to the depth of cut. From there, they built eq. (4).

$$R_a = 0.471\, h_m \tag{4}$$

Krishna Kumar Saxena, *et al.* [15] followed the same method and assumptions as that of what Sanchit Kumar Khare *et al.* [14] performed, but they gave eq. (5).

$$R_a = 0.92\, h_m \tag{5}$$

Based on the analysis of studies on modeling - simulating the grinding process shows that the study of surface roughness predictions of grinding parts based on the probability analysis of the cutting process has many advantages. We can say so because ***Firstly***, the study is based on the probability theory to analyze the cutting process, which is suitable for the process of joining randomly cut, randomly distributed abrasive grains on the wheel surface. ***Secondly***, the surface roughness value calculated in that study is quite close to the experimental results in each study [3], [12], [13], [14] and [15]. ***Thirdly***, surface roughness prediction studies based on probability analysis of cutting processes have been published in recent years, specifically Hecker *et al.* [3] (2003), Sanchit Kumar Khare *et al.* [12] (2015), Sanjay Agarwal *et al.* [13] (2005), Sanchit Kumar Khare *et al.* [14] (2015), and Krishna Kumar Saxena *et al.* [15] (2016).

Meanwhile, the other studies were published from previous years, Lal *et al.* [4] (1975); Nakayama *et al.* [5] (1968); Sato [6] (1955); Yang *et al.* [7] (1955); Zhou *et al.* [8] (2002); Basuray *et al.* [9] (1980) and Steffens [10] (1983).

However, in those studies, the surface roughness model has different values (eq. (1) - eq. (5)), because each author has different assumptions when building a model in their research. Therefore, in order to apply those studies to the prediction of surface roughness when grinding, it is necessary to primarily have empirical studies as the basis for selecting an appropriate model.

2. EXPERIMENT TO SELECT MODEL

2.1. Grinding Machine and Grinding Wheel

Grinding experiments were conducted in the APSG-820/2A surface grinding machine (Figure 1).

Figure 1: Grinding Machine.

The grinding wheels used in this study are an aluminum wheel, 36A60LV, (Taiwan) and a CBN grinding wheel, HY-100#, (Korea). The outer diameter size x thickness x the inner diameter of the wheels are 180 mm x 13 mm x 31.75 mm, respectively.

2.2 Components

Workpieces in this work are SKD11, SUJ2, 3X13 and C45 steels (Figure 2). They are types of steel, which are often used for manufacturing and grinding technology. Those steels' compositions are listed in tables 1–4.

Table 1: Chemical Composites of SKD11 Steel

Element	C	Si	Mn	Cr	Mo	V	Al	Cu
Composite [%]	1.50	0.20	0.40	11.3	0.90	0.25	0.02	0.10

Table 2: Chemical Composites of SUJ2 Steel

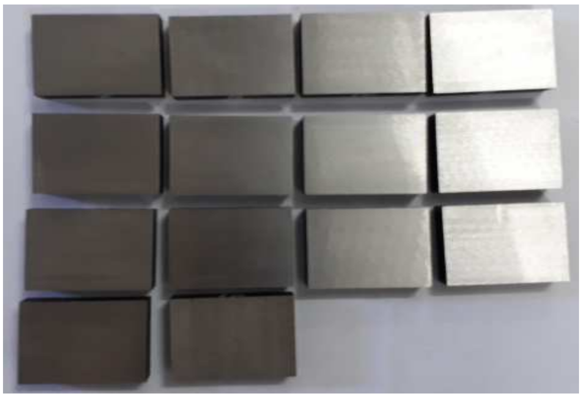
Element	C	Si	Mn	Cr	Al	Cu
Composite [%]	1.00	0.25	0.35	1.45	0.02	0.10

Table 3: Chemical Composites of 3X13 Steel

Element	C	Si	Mn	Cr	Ni	Mo
Composite [%]	0.35	0.4	0.25	13	0.2	0.20

Table 4: Chemical Composites of C45 Steel

Element	C	Si	Mn	Cr	Ni	Mo	V	Ti	B	Cu
Composite [%]	0.44	0.23	0.65	0.15	0.15	0.04	0.01	0.001	0.0004	0.21



3X13 Steel

SKD11 Steel

SUJ2 Steel

C45 Steel

Figure 2: Components.

2.3 Equipment

The surface roughness (R_a) of the part was measured by surface roughness tester, SJ-210 (MITUTOYO – Japan). The cut-off and evaluation lengths were fixed at 0.8 mm and 4 mm, respectively. The surface roughness was measured perpendicular to the cutting velocity direction and repeated three times following three repeated times of each cutting test. The average values of the measurements were evaluated.

Figure 3: Surface Roughness Tester SJ-201.

2.4 Experimental Plan

A series of experiments surface grinding for each of the workpiece–wheel combination with cutting parameters value showed in Tables 5 and 6 in which, v_w is the workpiece velocity and t is depth of cut.

Besides, the workpiece velocity and the depth of cut that were adjusted for each experiment, orderly, as shown in tables 5 and 6, the testing process was carried out with the value of other parameters as follows: Grinding wheel velocity (26 m/s). Before each experiment, the grinding wheel was dressed with a depth (0.01 mm) and the feed rate when dressing (150 mm/min). Cool irrigation technology using emulsion oil (10%), irrigation method with a flow (3.5 liters/minute).

Table 5: Experimental Plan, using CBN Wheel

Exp. Number	Cutting Parameters, using CBN Wheel	
	$v_w(m/\min)$	$t(\mathrm{mm})$
1	5	0.01
2	5	0.02
3	15	0.01
4	15	0.02

Table 6: Experimental Plan, using Aluminum Oxide Wheel

Exp. Number	Cutting Parameters, using Aluminum Oxide Wheel	
	$v_w(m/\min)$	$t(mm)$
1	8	0.05
2	8	0.035
3	15	0.05
4	15	0.035

3. RESULTS AND DISCUSSIONS

Surface roughness when grinding four types of steel SKD11, SUJ2, 3X13, C45by HY-100# grinding wheel and surface roughness when calculated by eqs. (1)–(5) are shown in figures 4–7(and in Tables 8–11 in Appendix 2).

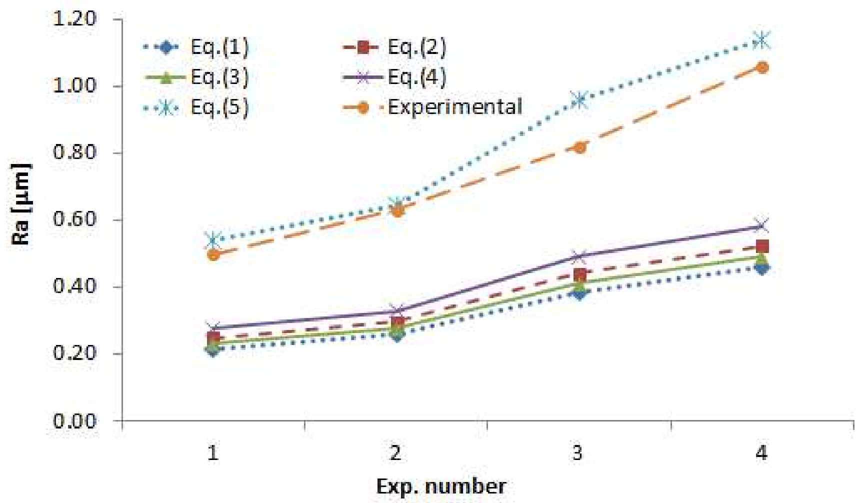


Figure 4: Comparison of the Predicted and Experimental Values of Surface Roughness (SKD11 Steel; HY-100# Wheel)

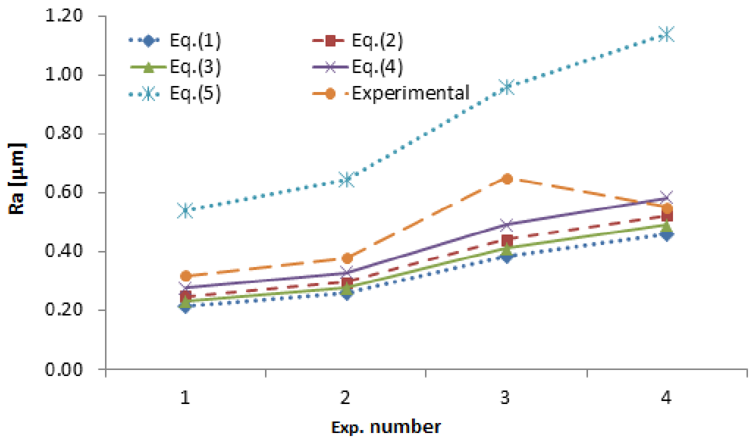


Figure 5: Comparison of the Predicted and Experimental Values of Surface Roughness (SUJ2 Steel; HY-100# Wheel).

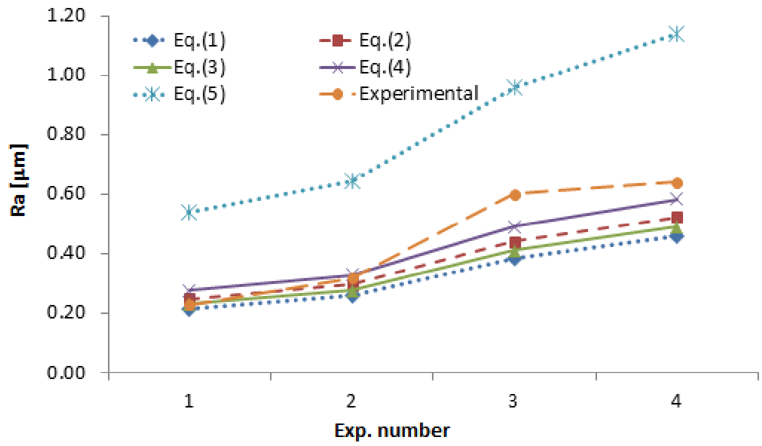


Figure 6: Comparison of the Predicted and Experimental Values of Surface Roughness (3X13 Steel; HY-100# Wheel).

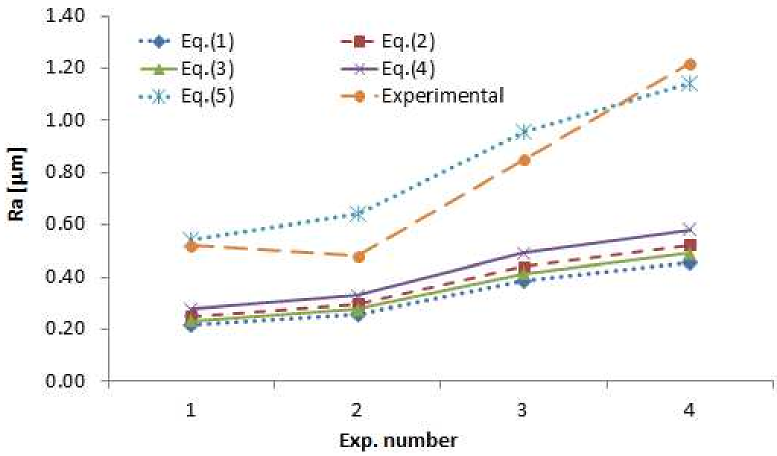


Figure 7: Comparison of the Predicted and Experimental Values of Surface Roughness (C45 Steel; HY-100# Wheel).

Similarly, surface roughness when grinding four types of steel SKD11, SUJ2, 3X13, C45 by 36A60LV grinding wheel and surface roughness when calculated by eqs. (1) - (5) are shown in figures - 11 (and in tables 12 to 15 in Appendix 2).

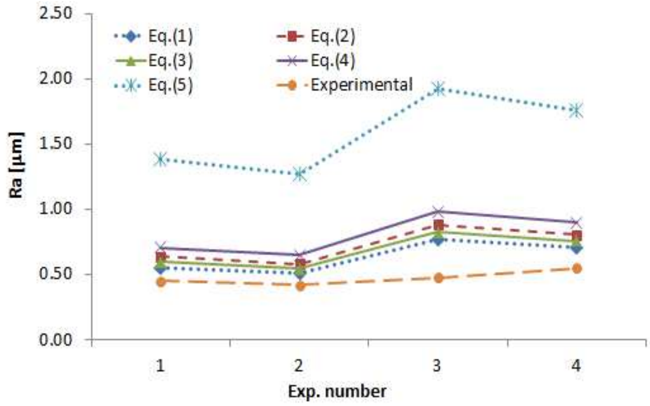


Figure 8: Comparison of the Predicted and Experimental Values of Surface Roughness (SKD11 Steel; 36A60LV Wheel).

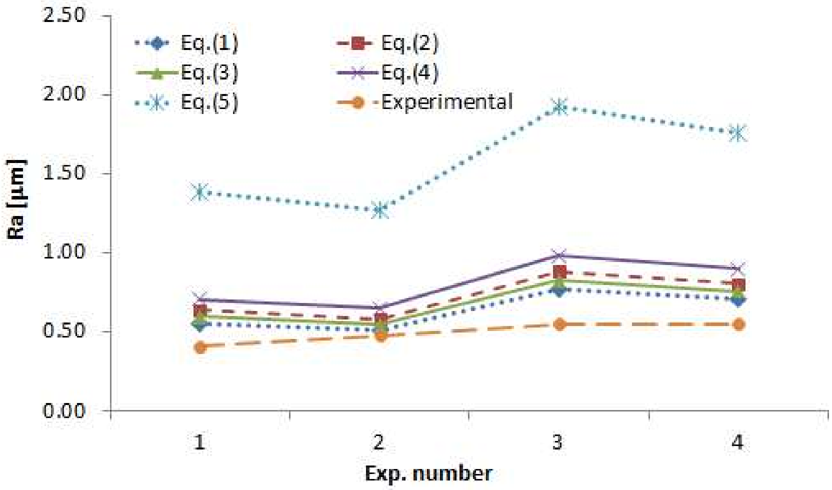


Figure 9: Comparison of the Predicted and Experimental Values of Surface Roughness (SUJ2 Steel; 36A60LV Wheel).

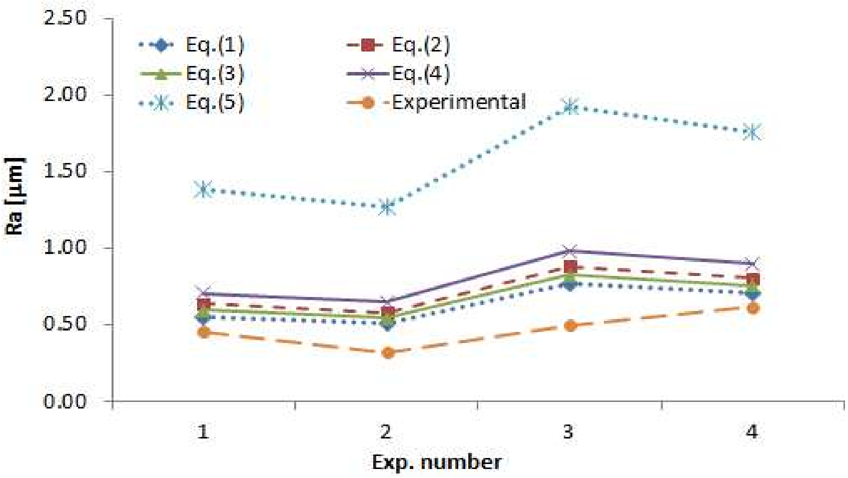


Figure 10: Comparison of the Predicted and Experimental Values of Surface Roughness (3X13; 36A60LV Wheel).

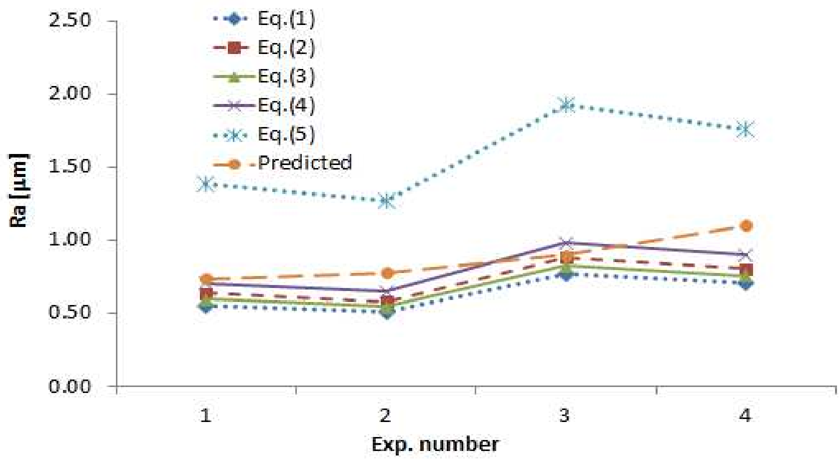


Figure 11: Comparison of the Predicted and Experimental Values of Surface Roughness (C45 Steel; 36A60LV Wheel).

From the results presented in figures (4) - (7), when using CBN wheel:

- Surface roughness value when grinding two types of steel SKD11 and C45 has the same value with surface roughness value when calculated according to eq. (4).
- For the case of SUJ2 and 3X13 steel, the roughness value of the surface when testing is similar to the surface roughness value when calculated according to eq. (5).

Similarly, the results presented in figures (8) - (11) show that when using aluminum oxide wheel:

- Surface roughness value when grinding three types of steel SKD11, SUJ2 and 3X13 has the same value with surface roughness value when calculated according to eq. (1).
- For the case of grinding C45 steel, surface roughness value in the experiment is similar to the surface roughness value when calculated according to eq. (5).

4. CONCLUSIONS

This study has conducted experimentally and selected the model of surface roughness prediction for each case when grinding four types of steel SKD11, SUJ2, 3X13 and C45 with aluminum oxide grinding wheel and CBN grinding wheel. The use of a surface roughness predictive model for each case allows reducing the time to adjust the machine, test-machining time, contributing to improving the efficiency of the grinding process.

5. ACKNOWLEDGMENTS

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APPENDIX 1

h_m is the undeform chip thickness in grinding processes.

$$h_m = 2\sqrt{\frac{1}{N}\frac{V_W}{V_G}\sqrt{\frac{t}{d_e}}}, \tag{6}$$

where

V_G - The grinding wheel velocity.

V_W - The workpiece velocity.

t – The grinding depth.

d_e - The equivalent grinding wheel diameter, which is determined by eq. (7):

$$d_e = \frac{d_G . d_W}{d_G \pm d_W} \tag{7}$$

In eq. (7), the negative sign applies for internal grinding. d_G, $d_W$are the grinding wheel diameter and workpiece diameter, respectively. For the surface grinding processes, $d_W \rightarrow \infty$, so $d_e = d_G$.

r–The ratio of the chip width to the thickness. N- is the number of active grits per unit area. The value of N is calculated by eq. (8).

$$N = 4f\frac{1}{d_g^2}\frac{1}{\sqrt[3]{\left(\frac{4\pi}{3V_g}\right)^2}} \tag{8}$$

where

f – The fraction of grinding grains involved in active grinding process.

d_g - The diameter of the grinding particle. d_g is determined by eq. (9).

$$d_g = \frac{15.2}{M}, \tag{9}$$

where M is an indicator of the graininess of the grinding wheel. This is the number of sieve holes per square inch of the sieve.

V_g - the volume ratio of the grinding grains in the grinding wheel. The value of V_g depends on the structure of the grinding wheel (S). With the common grinding wheel (the structure number is from 0 to 14), the value of V_g is determined by eq. 10. Besides with the diamond grinding wheel and CBN grinding wheel, the value of V_g is determined according to the sign of the grinding grain concentration, as listed in table 7.

$$V_g(\%) = 2(32eS) \tag{10}$$

Table 7: Relationship between Diamond/CBN Wheel Concentration and Grain Content

Concentration	25	50	75	100	125	150	175	200
V_g(%)	6.25	12.50	18.75	25.00	31.25	37.50	43.75	50.00

APPENDIX 2

Table 8: Predicted and Experimental Values of Surface Roughness (SKD11 Steel; HY-100# Wheel)

Exp. Number	Surface Roughness					
	Eq. (1)	Eq. (2)	Eq. (3)	Eq. (4)	Eq. (5)	Experimental
1	0.22	0.25	0.23	0.28	0.54	0.5
2	0.26	0.30	0.28	0.33	0.64	0.63
3	0.39	0.44	0.41	0.49	0.96	0.82
4	0.46	0.52	0.49	0.58	1.14	1.06

Table 9: Predicted and Experimental Values of Surface Roughness (SUJ2 Steel; HY-100# Wheel)

Exp. Number	Surface Roughness					
	Eq.(1)	Eq.(2)	Eq.(3)	Eq.(4)	Eq.(5)	Experimental
1	0.22	0.25	0.23	0.28	0.54	0.32
2	0.26	0.30	0.28	0.33	0.64	0.38
3	0.39	0.44	0.41	0.49	0.96	0.65
4	0.46	0.52	0.49	0.58	1.14	0.55

Table 10: Predicted and Experimental Values of Surface Roughness (3X13 steel; HY-100# Wheel)

Exp. Number	Surface Roughness					
	Eq. (1)	Eq. (2)	Eq. (3)	Eq. (4)	Eq. (5)	Experimental
1	0.22	0.25	0.23	0.28	0.54	0.23
2	0.26	0.30	0.28	0.33	0.64	0.32
3	0.39	0.44	0.41	0.49	0.96	0.6
4	0.46	0.52	0.49	0.58	1.14	0.64

Table 11: Predicted and Experimental Values of Surface Roughness (C45 Steel; HY-100# Wheel)

Exp. Number	Surface Roughness					
	Eq.(1)	Eq.(2)	Eq.(3)	Eq.(4)	Eq.(5)	Experimental
1	0.22	0.25	0.23	0.28	0.54	0.52
2	0.26	0.30	0.28	0.33	0.64	0.48
3	0.39	0.44	0.41	0.49	0.96	0.85
4	0.46	0.52	0.49	0.58	1.14	1.22

Table 12: Predicted and Experimental Values of Surface Roughness (SKD11 Steel; 36A60LV Wheel)

Exp. Number	Surface Roughness					
	Eq.(1)	Eq.(2)	Eq.(3)	Eq.(4)	Eq.(5)	Experimental
1	0.56	0.64	0.60	0.71	1.39	0.45
2	0.51	0.58	0.55	0.65	1.27	0.42
3	0.77	0.88	0.83	0.98	1.92	0.48
4	0.71	0.81	0.76	0.90	1.76	0.55

Table 13: Predicted and Experimental Values of Surface Roughness (SUJ2 Steel; 36A60LV Wheel)

Exp. Number	Surface Roughness					
	Eq.(1)	Eq.(2)	Eq.(3)	Eq.(4)	Eq.(5)	Experimental
1	0.56	0.64	0.60	0.71	1.39	0.41
2	0.51	0.58	0.55	0.65	1.27	0.48
3	0.77	0.88	0.83	0.98	1.92	0.55
4	0.71	0.81	0.76	0.90	1.76	0.55

Table 14: Predicted and Experimental Values of Surface Roughness (3X13; 36A60LV Wheel)

Exp. Number	Surface Roughness					
	Eq.(1)	Eq.(2)	Eq.(3)	Eq.(4)	Eq.(5)	Experimental
1	0.56	0.64	0.60	0.71	1.39	0.46
2	0.51	0.58	0.55	0.65	1.27	0.32
3	0.77	0.88	0.83	0.98	1.92	0.50
4	0.71	0.81	0.76	0.90	1.76	0.62

Table 15: Predicted and Experimental Values of Surface Roughness (C45 Steel; 36A60LV Wheel)

Exp. Number	Surface Roughness					
	Eq. (1)	Eq. (2)	Eq. (3)	Eq. (4)	Eq. (5)	Experimental
1	0.56	0.64	0.60	0.71	1.39	0.74
2	0.51	0.58	0.55	0.65	1.27	0.78
3	0.77	0.88	0.83	0.98	1.92	0.90
4	0.71	0.81	0.76	0.90	1.76	1.10

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